

METHOD OF FABRICATING A SEMICONDUCTOR DIE WITH MICROLENSES

FIELD OF THE INVENTION

The present invention relates to a method of fabricating a semiconductor die with a microlens associated therewith. More particularly, the present invention relates to a method for fabricating a vertical channel guide optical via through a silicon substrate wherein the optical via can contain lens elements, a discrete index gradient guiding pillar and other embodiments.

BACKGROUND OF THE INVENTION

Optoelectronic systems used for optically communicating between devices typically consist of a driver, an optical light emitting device such as a VCSEL, light coupling elements such as mirrors, gratings and optical waveguides for transporting optical signals from one point to another. An assembly of such optoelectronic system comprises fabricating waveguides and coupling elements on top of a substrate such as a printed wiring board (PWB) and then attaching a VCSEL device on top of such a substrate. The optical light emitted from the VCSEL is coupled into a waveguide on the substrate and is guided in-plane from one side of the substrate to other devices. It is very difficult and often impractical to integrate all of the components of the optoelectronic system such as driver and VCSEL onto a PWB substrate especially when the operating frequencies are beyond the GHz range. An alternate substrate such as silicon eases many of the integration complexities and provides a very high speed solution. A high performance computing system can be created by compactly integrating high speed driver and VCSEL components on a silicon substrate and maintaining optical communication through waveguides on the PWB. This scheme requires being able to couple light from one side of the silicon substrate to the other so that it can be coupled to a waveguide on the PWB.

The present invention enables crucial integration of optical and electronic components on a single substrate that is needed for inter chip optical communication through a backplane. This is done by being able to effectively couple light (used for optical communication) from sources mounted on one side of the substrate to waveguiding elements that may be located on the other side of the same substrate or a completely independent substrate.

SUMMARY OF THE INVENTION

The object of the present invention is to provide a means of transferring, coupling and or focusing light from an EO device on the top of a semiconductor substrate through the substrate to a waveguiding medium below the substrate.

It is understood that the same elements may also be used to transfer or couple from the waveguiding medium below the semiconductor substrate up through the substrate to a photodiode on top for detection and conversion into electrical signals. Additionally, the same elements described may be used to transfer or couple light from a waveguiding medium at one surface of the substrate to another waveguiding medium on the opposite side of the substrate.

It is an object of this invention that the high alignment accuracies afforded by standard semiconductor fabrication processes are exploited such to obviate the need for active alignment of the optical coupling or light guiding elements.

Brief Description of the Drawings

FIGS. 1a-1d are sectional side views of an embodiment showing process steps to fabricate vertical channel guide optical via;

FIGS. 2a-2c are sectional side views of an alternate embodiment showing process steps to fabricate vertical channel guide optical via thru a silicon core;

FIGS. 3a-3d are sectional side views of an alternate embodiment showing process steps to fabricate electro-optical via;

FIGS. 4a-4d.2 are sectional side views of an embodiment showing process steps to fabricate vertical channel guide optical via with directing elements on the backside;

FIGS. 5a-5i are sectional side views of an alternate embodiment showing process steps to fabricate vertical channel guide optical via with lens elements;

FIGS. 6a-6d are sectional side views of an alternate embodiment showing process steps to fabricate vertical channel guide optical via with a discrete index gradient guiding pillar;

FIGS. 7a-7f are sectional side views of an alternate embodiment showing process steps to fabricate vertical channel guide optical via with discrete index gradient layers on a support pillar;

FIGS. 8 is a sectional view of an alternate embodiment showing an embedded gradient index microlens;

FIGS. 9 is a sectional view of an alternate embodiment showing a microlens etched in to the backside of the semiconductor die;

FIGS. 10a-10e are sectional views of an alternate embodiment showing attached microlenses;

FIGS. 11a-11b illustrates the use of an electro-optical module attached to a print circuit

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring to the drawings more particularly by reference numbers, sectional side views of process steps sequence to fabricate vertical channel guide optical via are shown in FIGS. 1a-1e. A via 10 may be formed by known processes in a silicon substrate 11 as shown in FIG. 1a.

While the examples herein disclose silicon as the substrate, other elements/compounds can conveniently form the substrate. For example, in addition to silicon, germanium, indium phosphide, silicon/germanium, gallium arsenide, glass, quartz, sapphire and silicon carbide can be used to form the substrate.

The thru via 10 shown in FIG. 1a may be formed by first partially etching it in the silicon substrate 11 to the desired depth and later grinding silicon from the backside. Alternatively, the thru via 10 may be formed by completely etching it in the silicon substrate 11. The sidewall 12 of via 10 may be covered with low refractive index material to provide the function of a cladding layer 13 as shown in FIG. 1b. Via 10 with low refractive index material on its sidewall 12 may be filled partially or completely with high refractive index material 14 to provide the function of a core layer as shown in FIG. 1c. Suitable materials having a low refractive index which can be used in accordance with the various embodiments of the present invention are silicon dioxide or a polymer selected from the group consisting of acrylate polymers, siloxane polymers and vapor deposited polymers. Suitable materials having a high refractive index which can be used in accordance with the various embodiments of the present invention are: silicon dioxide or a polymer selected from the group consisting of acrylate polymers, siloxane polymers and vapor deposited polymers.

The terms "low" and "high" are used to describe the relative index of refraction of material. When a low index of refraction material is adjacent to a relatively high index of refraction material, light approaching the interface from the higher index material side intersecting the interface under the critical angle is internally reflected as defined by Snell's Law. Thus for a ray of light refracted at a surface separating two media, the ratio of the sine of the

angle of incidence to the sine of the angle of refraction is constant and is known as the angle of refraction for the two media. In this way, light is guided within "high" index of refraction materials when surrounded by relatively "low" index materials. The "core" of light guiding elements is therefore selected to be formed from materials possessing a high index of refraction, while the "clad", or surrounding materials, are selected to be low index of refraction materials. In the present invention it happens that the core and the clad materials can be identical; i.e., silicon dioxide or a polymer selected from the group consisting of acrylate polymers, siloxane polymers and vapor deposited polymers.

The emphasis is not on the material *per se*, but rather the index of refraction possessed by the two materials which are adjacent to each other in the system. In the present invention, the index difference (Δn) between high and low index of refraction material can vary between about 0.01 and about 2, depending on specific system design. For example, a high index core material may have a refractive index of 2, whereas the complimentary low index material may have an refractive index of 1.5.

An optical communication device 15 is aligned with the via, and is attached on top of the vertical guide optical via as shown in FIG. 1d. This embodiment may be employed when it is desired to guide or couple optical signal from one side of silicon substrate to the other by using a core/clad vertical waveguide structure. In this embodiment, an object is to maintain the spot size through the silicon substrate 11 using the difference in the index of refraction between the core layer and the clad layer.

There are light emitting and receiving elements which are aligned to the vertical optical guide. In all of the embodiments disclosed herein, the light emitting element can be a light emitting carbon nanotube, vertical cavity surface emitting laser (VCSEL), light emitting diode (LED), edge emitting laser, external laser source, wave guiding element and optical fiber. Suitable light receiving elements are a photodetector and a photoreceiver.

FIGS. 2a-2c are sectional side views of an alternate embodiment of the present invention showing process steps to fabricate a vertical channel guide optical via thru silicon substrate 21.

Several of the embodiments of the present invention employ “annular vias.” As used herein, an “annular via” refers to the volume generated when a rectangle of desired base is rotated about a vertical central axis which central axis is the diameter in the center of a “core” element.

Annular via comprising 20 and 20' may be etched in silicon 21 as shown in FIG. 2a. Annular via comprising 20 and 20' is formed to obtain the desired diameter silicon post 22 in its center surrounded by an annulus of desired dimensions. The annular via comprising 20 and 20' may be partially etched into silicon. The sidewalls 23 of the annular via comprising 20 and 20' may be covered with a low refractive index material to provide the function of a cladding layer 24 as shown in FIG. 2b. For the purpose of this embodiment, any remaining volume of the annular via may be filled with suitable optical, electrical or dielectric material, or it may be left unfilled. Typical examples of such optical materials are optically transparent polymers such as acrylates and siloxanes. Typical electrical materials are conductive copper paste, and typical dielectric materials known in the art are dielectric polymers such as epoxy polymers or polyimide.

An optical communication device 26 may be aligned and attached on top of the vertical guide optical via 20, 20' as shown in FIG. 2c. This embodiment may be employed when it is desired to guide or couple optical signal of suitable wavelength from one side of silicon substrate 21 to the other by using silicon as a core material 21. In this embodiment, light is guided with controlled divergence through substrate 21. In this embodiment, it is assumed that the light wavelength is transparent in silicon via clad with polymer or is a nitride annular ring filled with polymer using materials noted above.

FIGS. 3a-3d are sectional side views of an alternate embodiment showing process steps to fabricate an electro-optical via. Annular via 30 is etched in silicon substrate 31 as shown in

FIG. 3a. Annular via 30 is formed to obtain desired diameter silicon post 32 in its center surrounded by an annulus of desired dimensions. Annular via 30 may be partially etched into silicon 31. The sidewalls 33 of annular via 30 may be partially covered with a low refractive index material to provide the function of a waveguide cladding layer 34 as shown in FIG. 3b. Sidewalls 33 of annular via 30 may be partially covered with an electrically conductive material 35, as listed above to provide the function of carrying electrical signal as shown in FIG. 3b. For the purpose of this embodiment, any remaining volume of via 30 may be filled with suitable optical, electrical, or dielectric material of the type detailed above, or it may be left unfilled.

As shown in FIG. 3c, an electrical connection to deposited electrically conductive material 35 in via 30 may be formed by forming a second via 36 by etching from the backside of the silicon substrate to the deposited electrically conductive material 35. Another electrically conductive material 37, such as solder is deposited from the backside of the silicon substrate to allow the complete assembly to be attached to a foreign substrate 38, such as an FR-4 board, ceramic or any other similar type of substrate with complimentary electrically conductive signal lines 38'.

During the process of forming an electrical connection, the silicon substrate may be temporarily attached to an adhesive substrate such as commercially available sheet adhesives or other substrate. Additional photolithographic processes may be performed on the backside of silicon substrate. These processes may involve defining a pattern, etching the silicon substrate, passivating the silicon substrate backside surface, forming electrical contacts by means of depositing, plating, or screening metals or otherwise electrically conductive material 37 such as solder. An optical communication device 39 may be aligned and attached on top of electro-optical via as shown in FIG. 3d. This embodiment may be employed when it is desired to guide or couple optical signals of suitable wavelength from one side of silicon substrate to the other by using silicon as a core material. The embodiment is further employed when it is desired to establish an electrical connection from one side of silicon substrate 31 to the other through the same via.

FIGS. 4a-4d.2 are sectional side views of an alternate embodiment showing process steps to fabricate a vertical channel guide optical via 40 through silicon substrate 41 where the back side 42 of via 40 is patterned to introduce refractive (e.g. lens) or diffractive (e.g. grating) elements. Via 40 is formed by known processes in a silicon substrate 41 as shown in FIG. 4a. Though via 40 shown in FIG. 4a is formed by first partially etching it in silicon 41 to a desired depth and later grinding silicon from the backside 42. Through via 40 may alternatively be formed by completely etching it in silicon. In either event, through via 40 is then filled with a transparent material 43 as shown in FIG. 4b. The backside 42 of via 40 is then patterned and etched using any convenient known lithographic and etch process to form optical light directing elements 44 as shown in FIG. 4c. These elements may be refractive, such as a lens 45 shown in FIG. 4c.1, or diffractive, such as a grating 46 shown in FIG. 4c.2. An optical communication device 47 may be aligned and attached on top of optical via as shown in FIG. 4d.1 and FIG. 4d.2. This embodiment involving the optical communication device may be employed when it is desired to guide or couple optical signal of suitable wavelength from one side of silicon substrate 41 to the other by unguided transmission through transparent media 43 in the silicon substrate to optical directing elements at the bottom side of optical via 40.

FIGS. 5a-5i are sectional side views of an embodiment showing the process steps to fabricate vertical channel guide optical via 50 through silicon substrate core 51 where a lens is incorporated into via 50. There are two processes to form such a structure shown separately in FIGS. 5a-5e and FIGS. 5f-5i. In the first of these process sequences, via 50 is formed in a silicon substrate as shown in FIG. 5a using any known process. Through via 50 shown in FIG. 5a is formed in a series of steps. First, the via is partially etched in silicon substrate 51 to desired depth using a known process. The process to form the via in question is designed to form an inherently curved surface at the bottom of the etched portion of via 50. The intent of this embodiment is to use this curved surface as a lensing element. A thin layer of etch resistant material 52 is then deposited as shown in FIG. 5b.

The key property of the aforementioned materials is that they are resistant to processes used to etch silicon. Many materials can be chosen for this layer 52, including polymers such as polyimide or vapor deposited polymers and inorganic layers such as silicon nitride. Etch

resistant material 52 may be optically transparent as well. If this material is not optically transparent, this layer must be removed prior to use (step not shown). Preferably, a silicon nitride layer or silicon oxide layer may be used as the “etch stop” layer depending on the process used in further steps to etch the silicon. Via 50 is then filled to the surface thereof with transparent material 53 as shown in FIG. 5c. Suitable materials having low optical attenuation should be used for this purpose in accordance with the various embodiments of the present invention. Examples of such materials are acrylate or siloxane polymers.

A planarization step (not shown) may be used to produce a planar surface at the top of the via, but may not be needed because of the use of an optical underfill such as a transparent epoxy. The back side 54 of silicon substrate 51 is then etched to open the bottom side 55 of via 50. This etch may be a dry etch or a wet etch, and must stop on the etch stop layer 52 on the curved surface 56 at the base of via 50 shown in FIG. 5d. An optical communication device 57 is then aligned and attached on top of the vertical guide optical via as shown in FIG. 5e.

In the second of these process sequences, via 50 is formed as before by known processes in a silicon substrate core 51. Via 50 is first partially etched in the silicon substrate 51 to desired depth using a known process. A thin layer of etch resistant material 52 is then deposited. The key property of this material is that it is resistant to processes used to etch silicon. A silicon nitride layer or silicon oxide layer may be used for this depending on the process used in further steps to etch silicon. These steps are shown before in FIG. 5a and FIG. 5b. If the etch process does not result in a surface at the bottom of via 50 appropriate for lensing, an alternate process may be used to form the curved surface. Via 50 is filled with a “sacrificial” material 58. This “sacrificial material” 58 possesses an appropriate surface tension that when placed in contact with etch resistant material 52, naturally forms a meniscus 59 in via 50 as shown in FIG. 5f. The curvature of meniscus 59 is regulated by controlling the surface tension of the via wall 50 and the surface tension of sacrificial material 58. A second thin layer of etch resistant material 520 is then deposited. The key property of material 520 is that it is resistant to processes used to remove sacrificial layer 58 and may or may not be the same etch material as first etch resistant layer 52. The etch resistant material 520 may be optically transparent as well. If this material is not

optically transparent, this layer must be removed prior to use (step not shown). Via 50 is then filled to the surface of the via with a transparent material 53.

The deposition of the second etch resistant layer 520 and transparent material 53 is shown in FIG. 5g. A planarization step (not shown) may be used to produce a planar surface at the top of via 50, but may not be needed because of the use of an optical underfill. The back side 54 of the silicon substrate 51 is then etched to open the bottom side 55 of via 50. This etch may be a dry or wet etch, and must stop on the etch stop layer 52 at the base of via 50 as shown in FIG. 5g. Etch resistant layer 52 is then removed via a selective etch process, and the sacrificial layer 58 is removed. The process to remove sacrificial layer 58 may be wet (e.g. chemical etch or dissolution) or dry (e.g. plasma ashing or laser ablation). The surface remaining at the base of via 50 has the appropriate curvature and placement to be used as a lensing element. The curved surface formed by meniscus 59 acts as a lens.

An optical communication device 57 is then aligned and attached on top of the vertical guide optical via as shown in FIG. 5i. The embodiments shown in FIG. 5e and FIG. 5i may be employed when it is desired to guide or couple optical signal of suitable wavelength from one side of silicon substrate to the other by unguided transmission through a transparent media in the silicon substrate to lens within the via.

FIGS. 6a-6d are sectional side views of an alternate embodiment showing process steps to fabricate a vertical channel guide optical via through a discrete index gradient guiding pillar. Annular via 60 may be etched in a silicon substrate 61 as shown in FIG. 6a. The annular via is formed with a small diameter silicon post 62 in its center surrounded by a large annulus of desired dimensions. The annular via 60 may be partially etched into silicon. A series of layers 631, 632, 633, etc. are sequentially deposited with decreasing refractive index producing a radially decreasing index gradient as shown in FIG. 6b. Silicon oxynitride is appropriate for use to form these layers because of the ability to control the index of the deposited layer over a wide index range from 1.45 to 2.0. Various polymers such as polyimide or siloxane polymers or vapor deposited polymers can also be used. The layers are deposited sequentially with each

layer having a decreasing index until the diameter is sufficiently large to capture all of the light generated later during use. When the desired radial dimension of the pillar is attained the remaining open regions may be filled with lower index material or left open for use as an electrical through via connection. The top layer may be planarized using conventional chemical mechanical polishing tools easily available in most silicon processing lines as shown in FIG. 6c if needed. FIG. 6d demonstrates how light will be guided through via 60. The diameter of silicon post 62 should be less than or approximately equal to the projected diameter of the light guided. The intent of this embodiment is to use the small diameter silicon pillar 62 to guide the light to the base of the via using the radial index gradient in these deposited layers to assist in guiding the light, and to control the size of the beam as it passes through the optical via in the silicon substrate. This inherently assumes that the light must be of a wavelength capable of being transmitted through the silicon substrate

FIGS. 7a-7f are sectional side views of an alternate embodiment showing process steps to fabricate vertical channel guide optical via thru a discrete index gradient support pillar. Annular via 70 may be etched in a silicon substrate 71 as shown in FIG. 7a. The annular via is formed with a small diameter silicon post 72 in its center surrounded by a large annulus of desired dimensions. Annular via 70 may be partially etched into the silicon substrate 71. A series of layers 731, 732, 733, etc. are sequentially deposited with decreasing refractive index producing a radially symmetric index profile gradient as shown in FIG. 7b. In this instance, layers are deposited sequentially until the diameter of the via is large enough to capture all of the light which is focused on it. One possible index profile is shown in FIG. 7f.

Silicon oxynitride is appropriate for use in these layers because of the ability to control the index of the deposited layer over a wide index range of from about 1.45 to about 2.0. Various polymer such as polyimide or siloxane polymers or vapor deposited polymers can also be used. The layers are deposited sequentially with each layer having a decreasing index until the diameter is sufficiently large to capture all of the light generated later during use. A thick silicon dioxide layer may be thermally grown or vapor deposited as the first layer prior to sequentially depositing layers 731, 732, 733, etc. from silicon pillar 72. When the desired radial

dimension of the support pillar and guiding layers is attained, the remaining open regions are filled with material having a low refractive index.

The top layer may be planarized using conventional chemical mechanical polishing tools easily available in most silicon processing lines as shown in FIG. 7c if need. The bottom of the silicon substrate is planarized as shown in FIG. 7d. Planarization etch stop layers may be incorporated in the sequential build to assist planarization. FIG. 7e demonstrates how light will be guided through the via. The diameter of the silicon post should be much less than to the projected diameter of the light guided. The intent of this embodiment is to use this small diameter silicon pillar to support the subsequent layers that are used for guiding the light. This optical via structure is appropriate for use with many wavelengths, even $< 1 \mu\text{m}$, as the light is guided around the silicon pillar and not through the pillar and is therefore not limited by the absorption of light in the material of the pillar. The intent is to minimize the contribution of the silicon pillar to the cross sectional area of the via that the light interacts with minimal and in that way the light is guided by the index layers around the pillar.

Though not exclusively mentioned in these embodiments, electrical wiring levels may be built on the silicon substrate prior to attaching any optical devices. Other form of electrical devices such as ICs, passive devices, or other devices may also be attached on the silicon substrate and interconnected by use of the wiring levels on the substrate. Additionally, the via structures described above may be formed from the top or the bottom side of the silicon substrate, implying the ability to make such structure in both orientations to light transmitting and receiving surfaces.

FIG 8 shows a cross sectional view of an alternate embodiment showing an integrated gradient index optical via. In this embodiment a thru via 80 in a silicon substrate 81 is filled with a material 82 or set of materials whose indexes gradually vary to give a microlens structure as shown in FIG 8. Such via may have the highest index at the via center and gradually decreasing index radially outward from the center of via. This axial radial gradient may take on various

forms. As an example, for the case where it is desired to collimate the light from a VCSEL 83, an axial radial gradient described by the following equation may be used.

$$n(r) = n_0 + nr^2$$

where the center index $n_0 = 1.54$, the gradient parameter $nr = -10$, and where the radius $r = 0$ to 0.125 mm. By changing the nature of the radial gradient it is also possible to focus the light from a VCSEL directly into a waveguide structure.

The structure embodied in FIG. 8 is fabricated by first etching a thru via 80 in the silicon substrate 81. Via 80 is then filled with an optically transparent medium 82 such as a sol-gel material. Through the process of material densification, using for example a focused laser beam, the index of the transparent medium may be altered to obtain the desired radial index profile within the via. Alternatively, the transparent optical medium's index may be altered by means of ion diffusion techniques.

FIG 9 shows a cross sectional view of an alternate embodiment of a semiconductor die 91 with a microlens formed on its surface. In this embodiment a spherical or aspherical lens is formed or etched into one side or both sides of the silicon or semiconductor die 91. Silicon is essentially transparent for wavelengths greater than 1 micron. As shown, the VCSEL 92 and or photodiode may be mounted one side of the silicon substrate and the microlens 93 formed on the other.

As an example, for a 1.3 micron wavelength VCSEL, with a VCSEL to microlens distance of 500 microns, and with a microlens radius of 360 microns the light from the VCSEL is approximately collimated by the microlens.

The microlens may be fabricated by standard semiconductor fabrication means. For example a gray scale mask may be used to expose a layer of photoresist on the Si substrate, followed by a RIE process to define the microlens surface.

FIGS 10a-10e show cross sectional views of an alternate embodiment of a semiconductor die with attached microlenses. In FIG 10a a through via 100 is etched in the silicon substrate 101 and a microlens array 102 is attached in order to collimate or focus the light from the VCSEL array 103. In FIG 10b the microlens array 102 is recessed within silicon substrate 101. In FIG 10c the microlens array 102 is attached directly to the VCSEL 103 or photodiode array and then inserted into the silicon substrate 101 thru via 100. In FIG 10d microlens array 102 is inserted into the through via 100 and is held in position by the via. In FIG 10e the microlens array 102 is inserted from the top into the through via 100.

In all of these embodiments, the objective is to take advantage of the precision of the silicon etch process and define feature (such as the thru via) to which the attached microlens array may be referenced. By having these highly accurate reference features the microlens array may be simply and accurately attached to the silicon substrate in a passive manner, leading to a highly accurate, low cost assembly.

FIGS 11a-11c illustrate how the silicon carrier electro-optic module may be used in a system. In FIG 11a electrical signals in the printed circuit board 1100 approach the silicon carrier 111. These signals proceed through the electrical vias 110 to the top side of silicon carrier 111. Wiring on the top of the carrier conducts these signals to a VCSEL array 112. These electrical signals are then transposed by the VCSEL array into optical signals. Light from VCSEL array 112 is then focused by the microlens array 113 towards a waveguide structure 114 that is embedded in printed circuit board 1100.

Waveguide structure 114 then channels this light across printed circuit board 1100 to a receiving electro-optic module to be converted back to electrical signaling. The receiving electro-optical has a similar structure as that shown with a photodetector (PD) in place of the VCSEL. The optical via in embodiments 1 through 10 herein in the electro-optical module fabricated in silicon performs the critical function of conveying the light energy from VCSEL 112 to the waveguide structure 114 to a photodetector on a similar electro-optical module.

In FIG 11*b* an alternate configuration is shown in which the microlens 115 in the electro-optic module collimates the light. A complementary microlens array 116 is embedded in the printed circuit board and focuses the light into the waveguide structure.

In Figure 11*c* an alternate configuration is shown in which an optical via 117 conducts the light from VCSEL 112 through the carrier substrate 111 and directly couples the light into a waveguide structure 114. For this coupling to be efficient the optical via 110 and waveguide structure 114 shall be in intimate contact.

While certain exemplary embodiments have been described and shown in the accompanying drawings, it is to be understood that such embodiments are merely illustrative of and not restrictive on the broad invention, and that this invention not be limited to the specific constructions and arrangements shown and described, since various other modifications may occur to those ordinarily skilled in the art.